Air Force Research Laboratory

Integrity ★ Service ★ Excellence

Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model Effort for the Integrated Global-Sun Model

LWS Heliophysics Science Technical Interchange Meeting 2014

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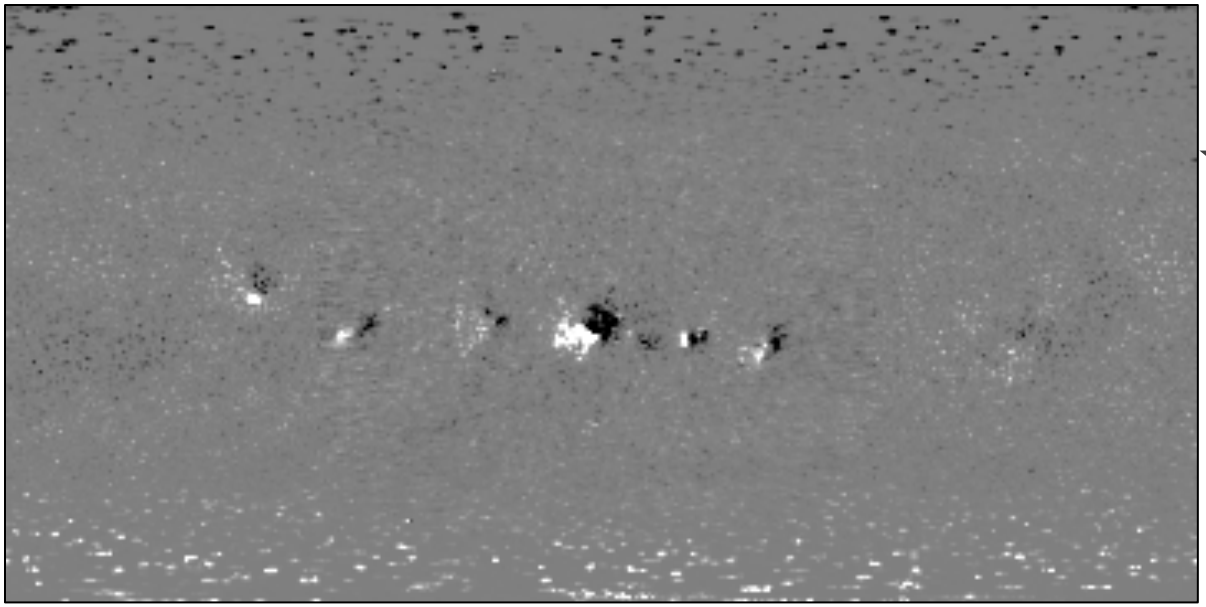
AFRL

Air Force Data Assimilative Photospheric Flux Transport (ADAPT) Model

1. Evolves the solar magnetic flux using well understood transport processes where measurements are not available.
2. Updates modeled flux with new observations using data assimilation methods - Rigorously takes into account model & observational uncertainties.



Sun's surface magnetic field (*movie length ~60 days*)

AFOSR Star Team!

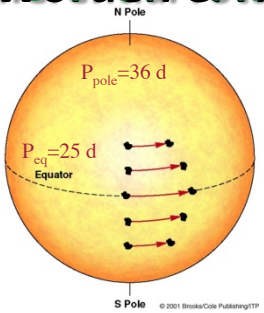
Provides more realistic estimates of the instantaneous global photospheric magnetic field distribution than those provided by traditional synoptic maps.

ADAPT Flux Transport Model

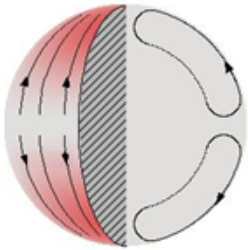
Overview: The ADAPT flux transport model (Arge et al. 2009, 2010, & 2013) is based on Worden & Harvey (2000), which *accounts for known flows in the solar photosphere.*

The modified Worden & Harvey (WH) model used in ADAPT includes:

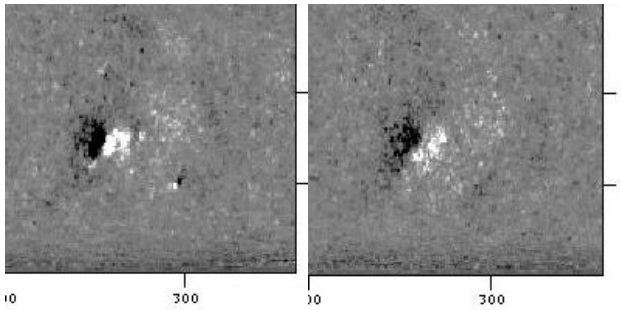
(1) Differential rotation



(2) Meridional flow



(3) Supergranular diffusion



(4) Random flux emergence

(5) Data assimilation of new observations (LANL)

(6) An ENSEMBLE of solutions representing the model parameter uncertainties

Data Assimilation

The ADAPT data assimilation method used: *Los Alamos National Laboratory (LANL) data assimilation framework.*

- **Efficient and flexible data assimilation code.**
- **Uses either an Ensemble Least Squares or Kalman filter techniques.**

1) Ensemble Least Squares (EnLS) estimation method:

- **Method used during initial testing and development.**
  - **Takes into account both model and data errors.**
  - **Does *not* consider spatial correlations.**

2) Ensemble Kalman filter (EnKF) method:

- **Recursive algorithm that automatically takes into account past correlations between different regions of the photosphere.**
- **Recently incorporated *Local Ensemble Transform Kalman Filter (LETKF)***
  - **Handles unique properties of solar magnetic field observations better.**

Data Assimilation with EnLS

- New observations are data assimilated using an ensemble least-squares (EnLS) estimation method:

$$X_a = X_f + \omega (y - H(X_f)),$$

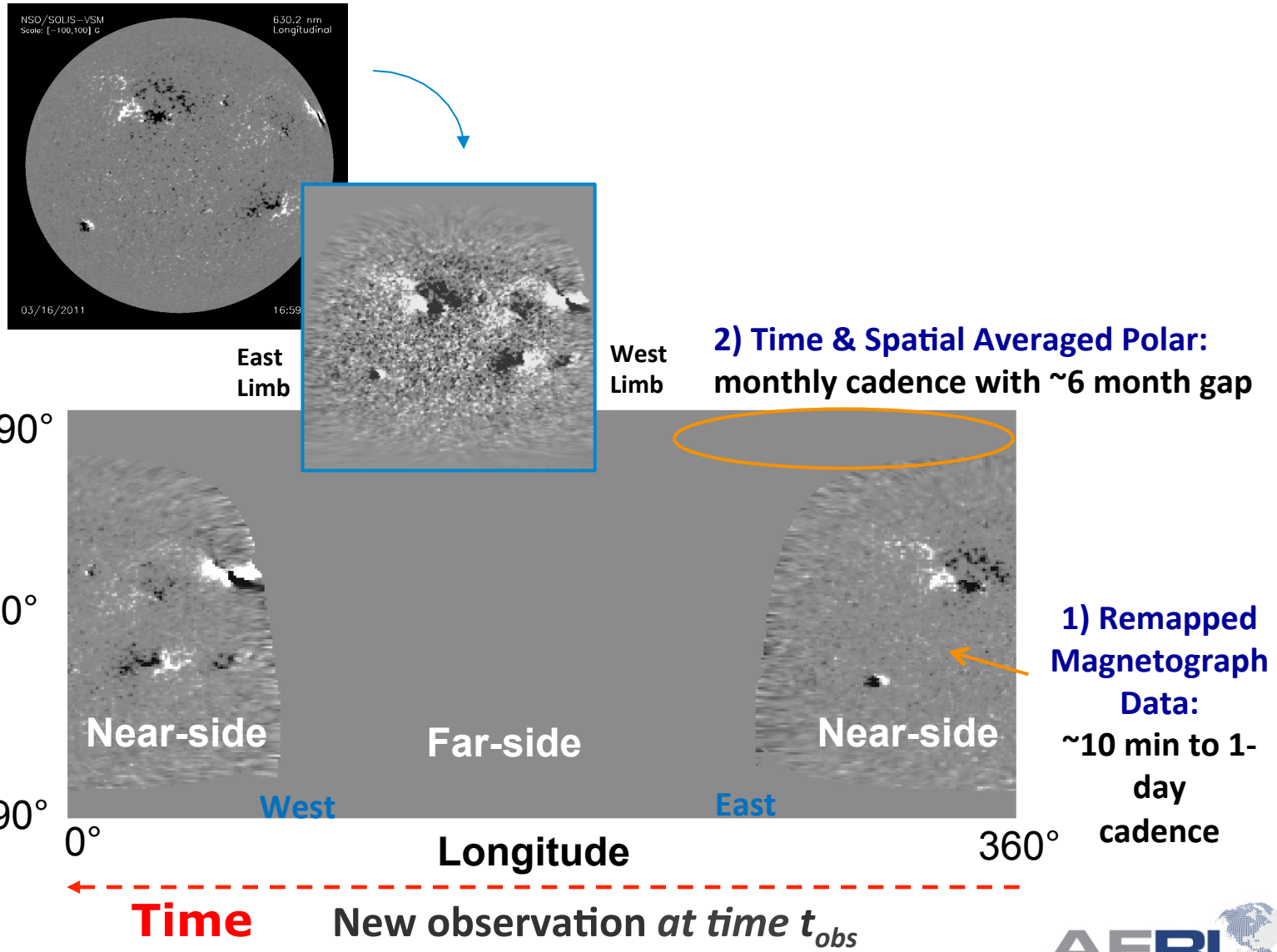
where X_a, X_f, ω, and y represent the analysis, model forecast, weight, and observation values respectively. And H is the observation operator, i.e., zero unless observed data. The weight, ω, is defined as:

$$\omega = \sigma_f^2 / (\sigma_f^2 + \sigma_y^2),$$

where σ_f^2 and σ_y^2 are the variances of the model forecast ensemble and observed data respectively.

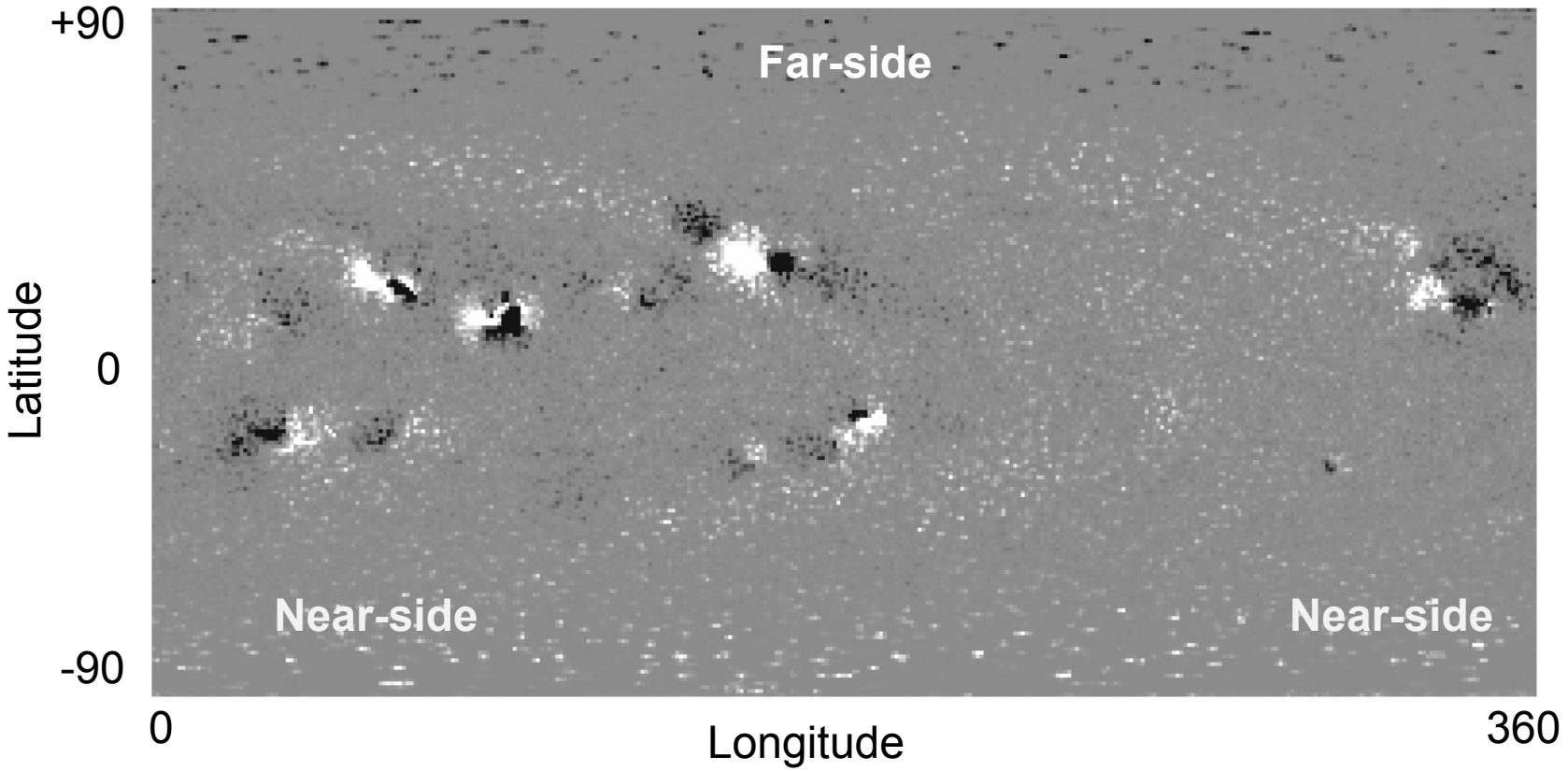
- *Currently, Humberto C. Godinez & Kyle Hickmann (LANL) are testing localized ensemble Kalman filtering with ADAPT.*

Global Maps: data sources



Example EnLS: model forecast

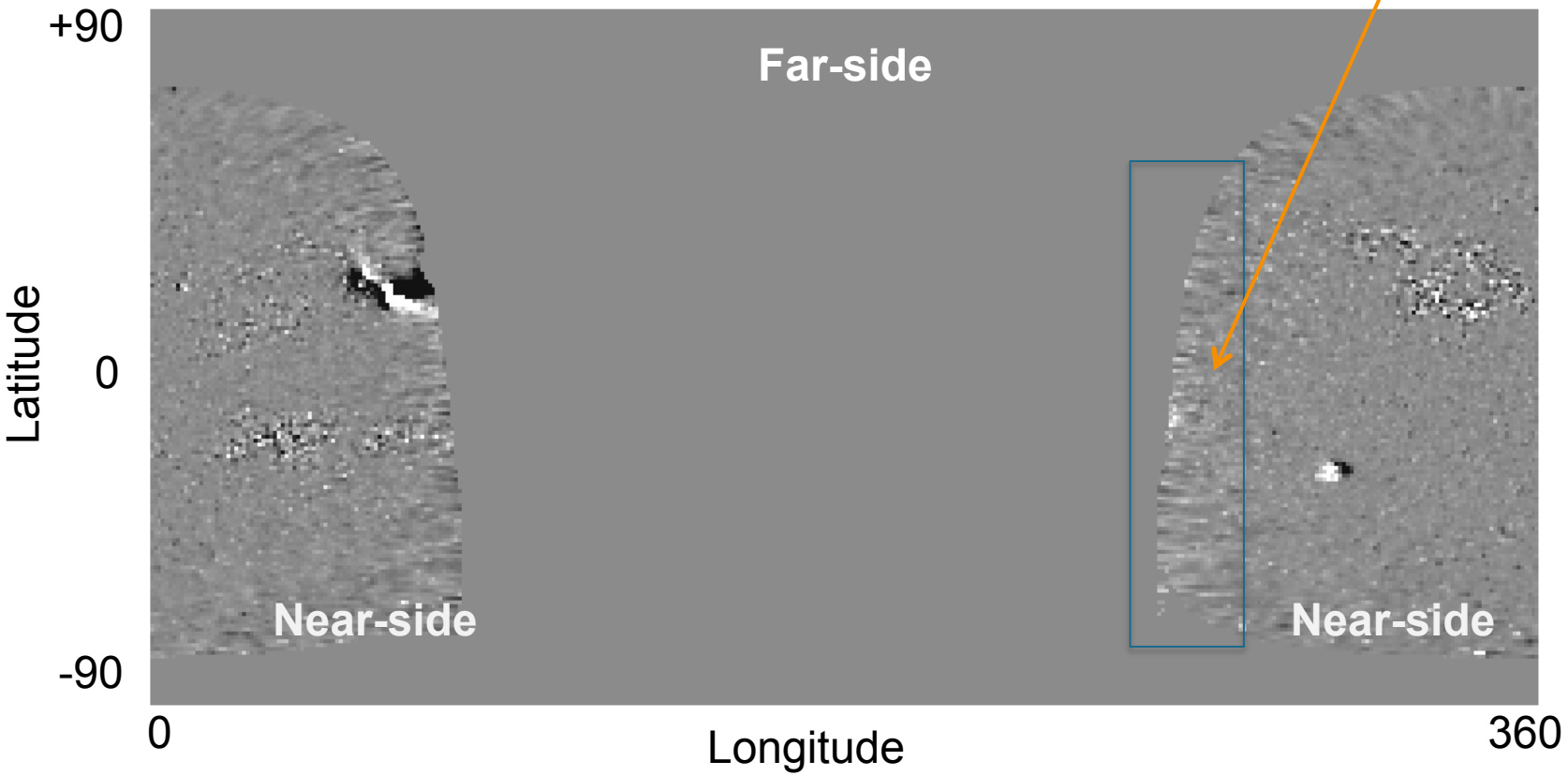
Example forecast realization from the ensemble, $\mathbf{X}_f$ (*at time* t_{obs}):



Example EnLS: innovation

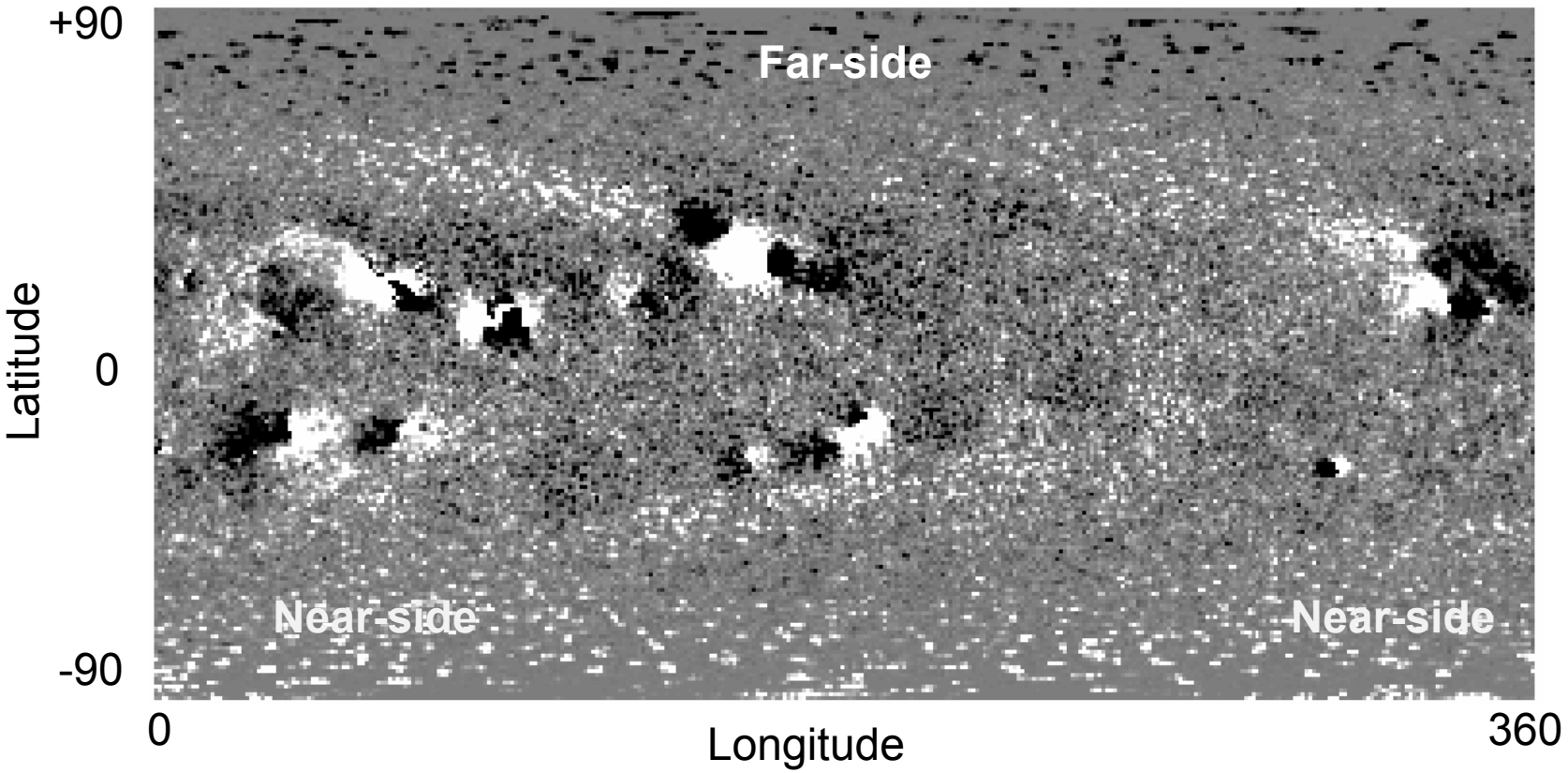
Innovation, ($\mathbf{y}$ – H($\mathbf{x}_f$)), *at time* t_{obs}:

Solar East-limb:
region of > 13-day temporal discontinuity;
leads to large field strength/polarity offsets



Example EnLS: analysis

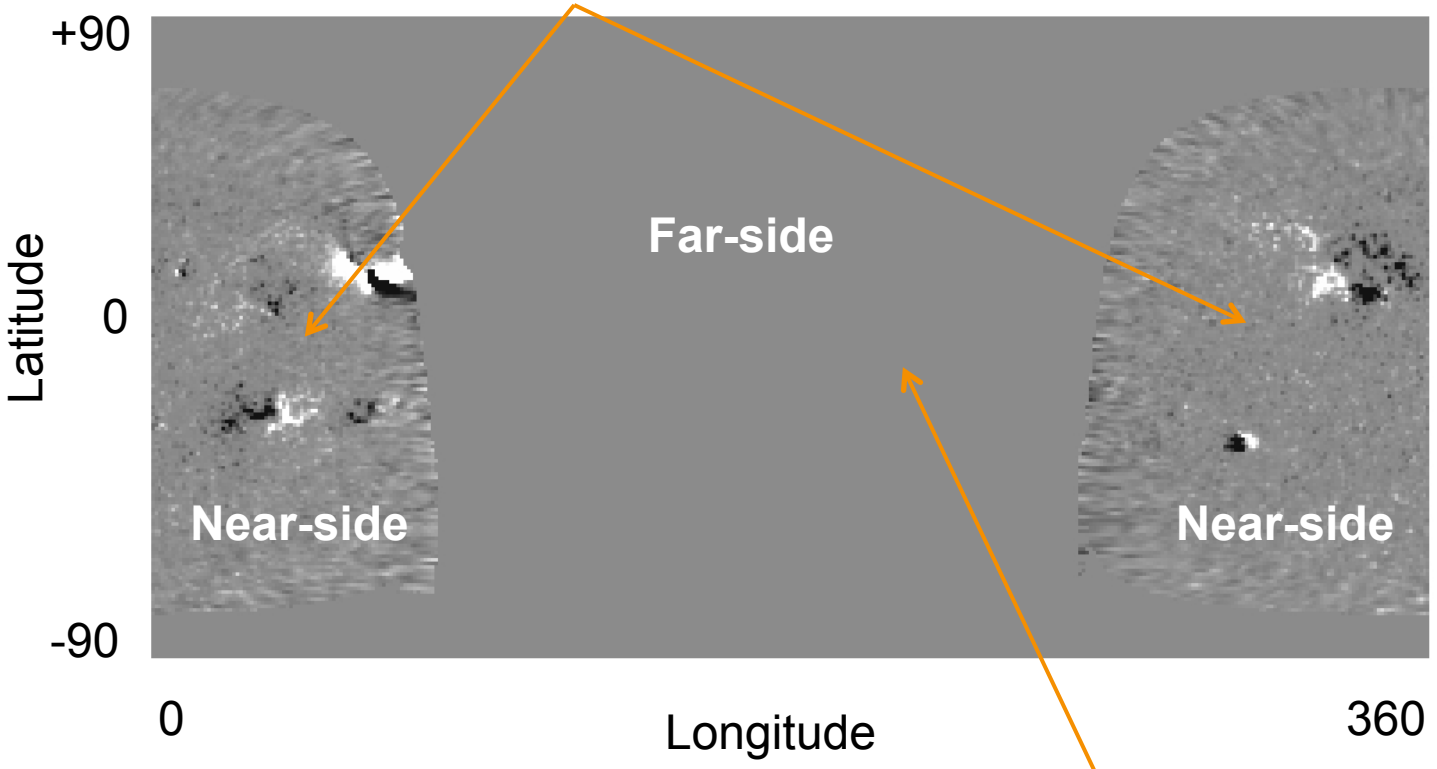
Analysis, X_f + ω (y – H(x_f)), example with 16 realizations (*at time* t_{obs}):



Helioseismic Data Sources

4) Subsurface Near-side Helioseismic |B| Data (< 1.5 days in advance): ~12 hr cadence

2) Polar (time & spatial averaged): monthly cadence w/ ~6 month gaps

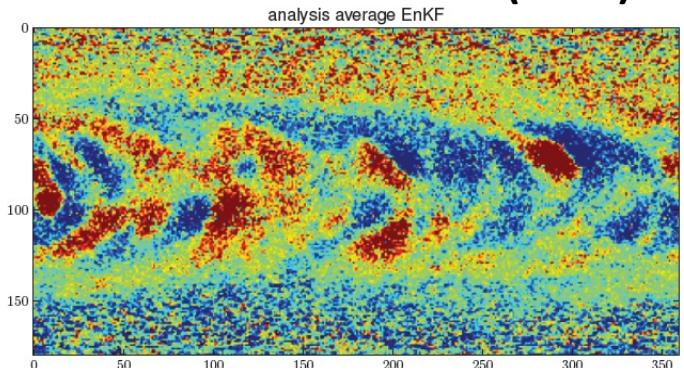


1) Remapped Magnetograph Data: ~10 min to 1-day cadence

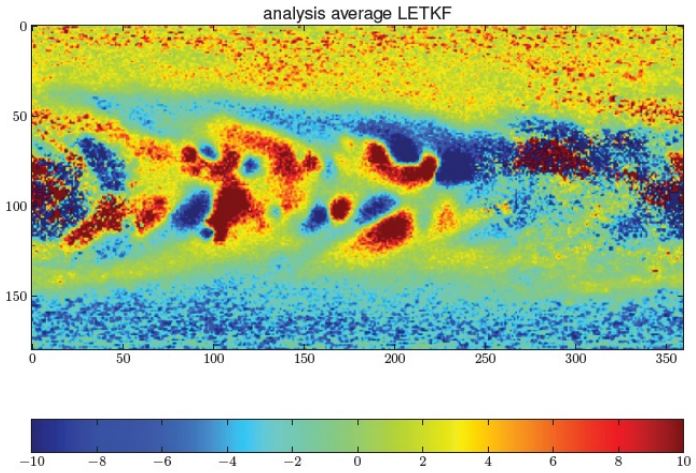
3) Farside Helioseismic |B| Data (for large active regions): ~12 hr cadence

Ensemble Kalman Filter (EnKF) vs Local Ensemble Transform Kalman Filter (LETKF)

Ensemble Kalman Filter (EnKF)



Local Ensemble Transform Kalman Filter (LETKF)

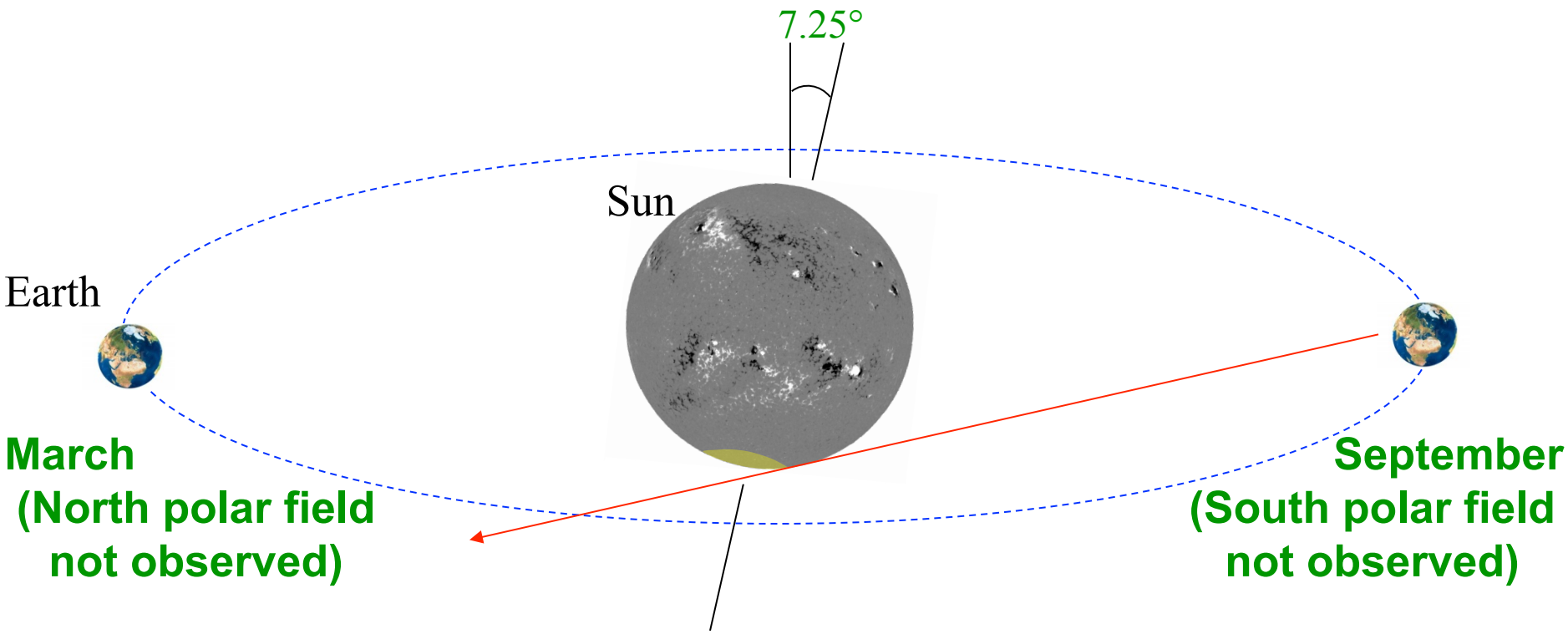


- A local ensemble transform Kalman filter (LETKF) implemented to suppress noise in analysis.
- Numerical results clearly show a better solution with LETKF than EnKF.
- Computation time for LETKF is high if done in serial, parallelization has been implemented.
- Model errors may be an issue, implemented an inflation technique to avoid filter divergence.

(Top) Sample ADAPT map with the standard EnKF implementation image). The effects of the spurious correlation are clearly visible (particularly at the poles) in the small spatial scale mixed polarity noise. (Bottom) ADAPT map using the new LETKF implementation.

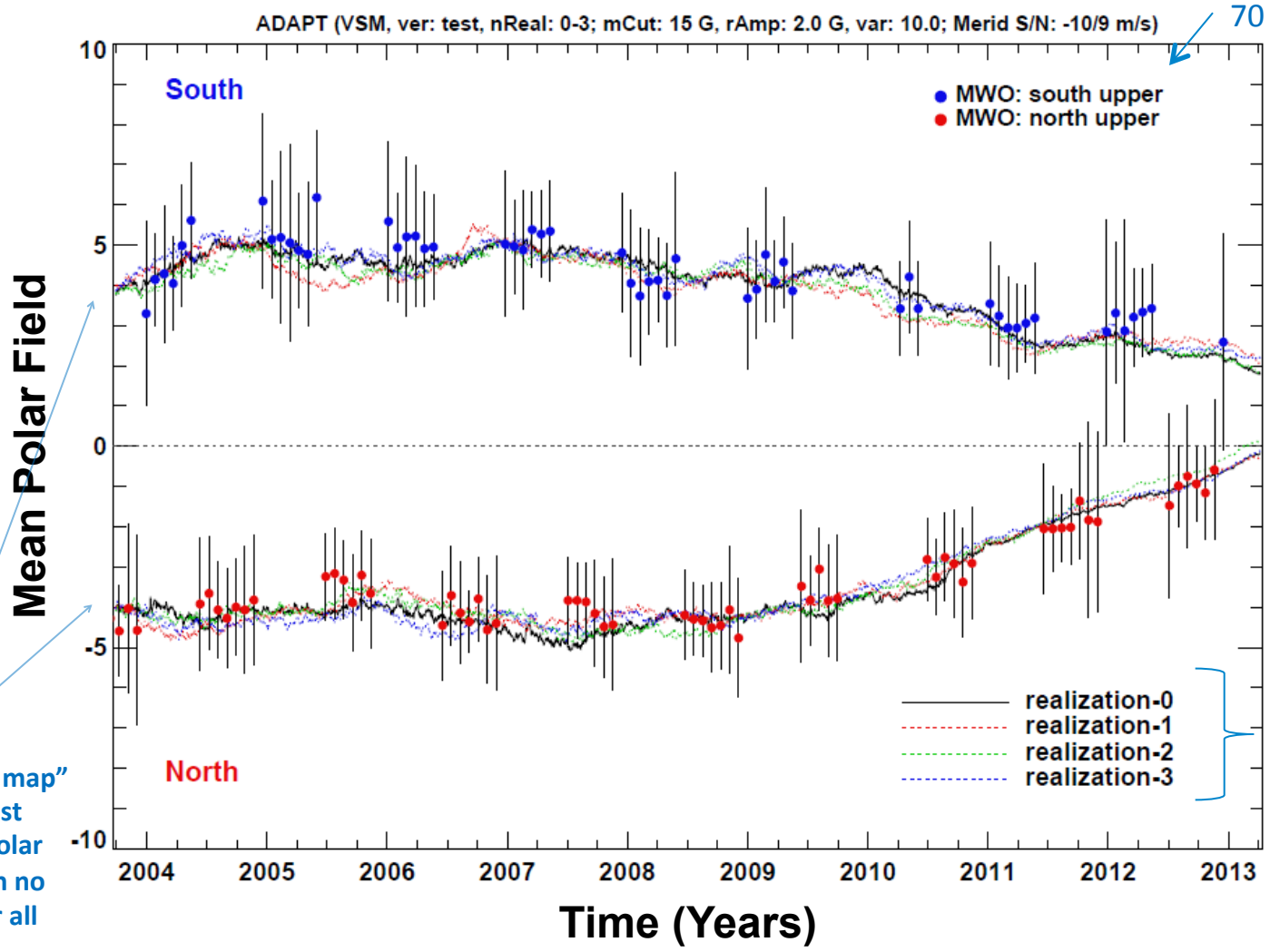
The Inclination of the Sun's Axis to the Ecliptic Impacts Measurements of the Photospheric Field

The Sun's rotational axis is inclined 7.25° to the ecliptic.



The Polar Fields are NOT observed for extend periods of time.
Coronal models are very sensitive to the values of the polar fields.

Observed vs ADAPT Predicted Polar Fields

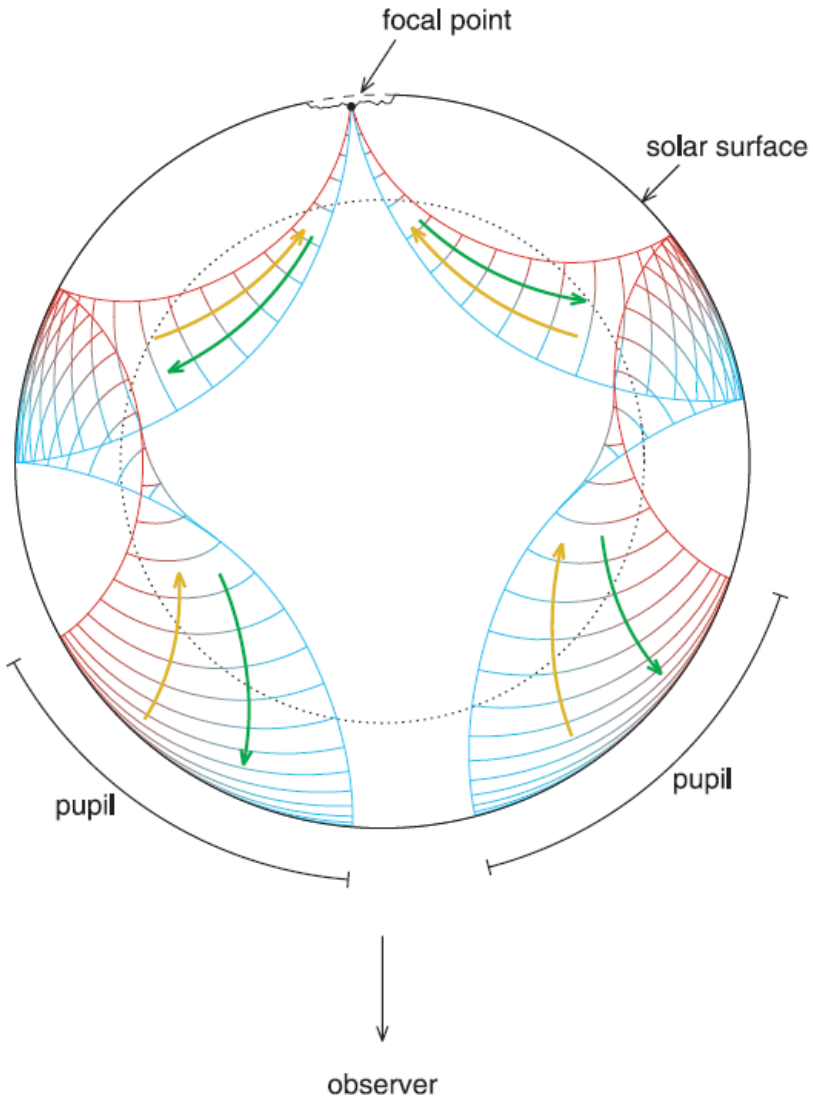


70 to 90 degrees

Identical model parameters

Note: initial "seed map" begins with the best estimates of the polar field strength, with no additional data for all future time steps.

Farside Active Region Detection



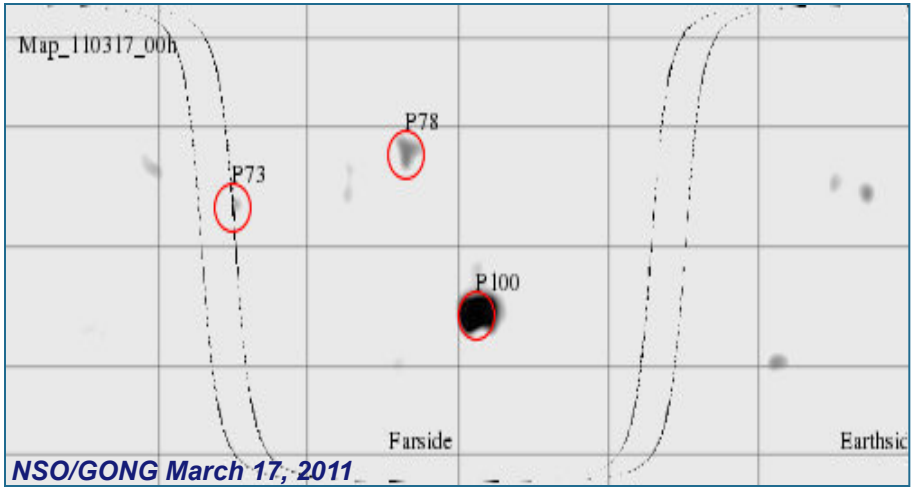
Farside detections are derived from helioseismic holography

- **LOS Doppler signal used to estimate the wave-field at any location in the solar interior at any given time.**
- **Farside images are based on ingression-egression correlations ("phase-sensitive" holography).**

Figure from Lindsey & Braun 2000, Science, 287, 1799

Incorporating Far-side Maps

Without far-side data, space weather forecasting models are reliant on the persistence & recurrence of past observations.



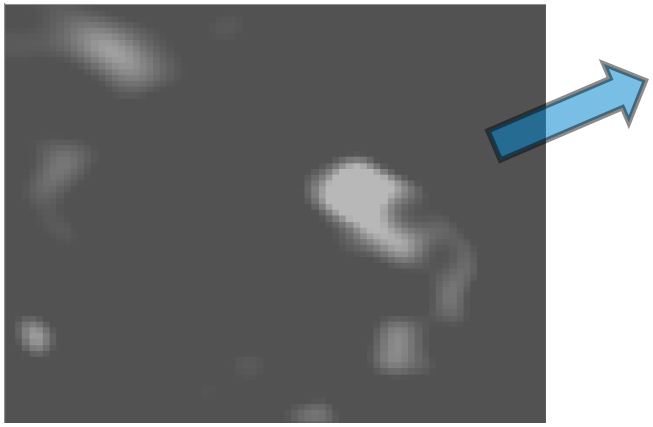
Far-side data assimilation requires a realistic estimation of the:

1. **magnetic field strength & uncertainty**
2. **position & uncertainty**
3. **simple polarity and tilt estimations (i.e., Hale's law & Joy's Law)**

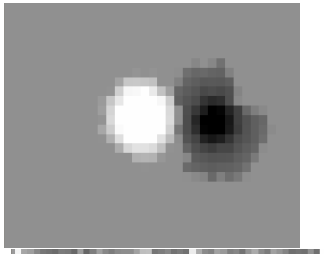
A "far-side ensemble" can be generated from these 3 factors.

Farside Polarity Estimation

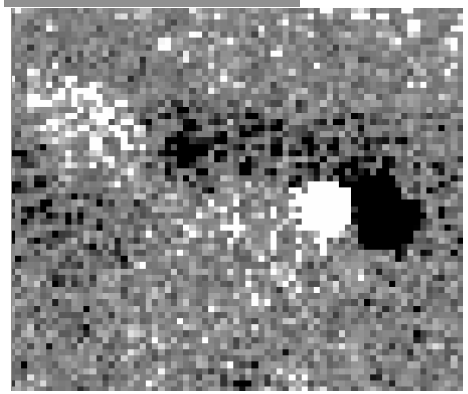
- Example polarity estimation derived from helioseismic phase data. Testing a polarity distribution model that is dependent on the farside signal strength & area:



Farside signal from NSO/ GONG (July 1, 2010)

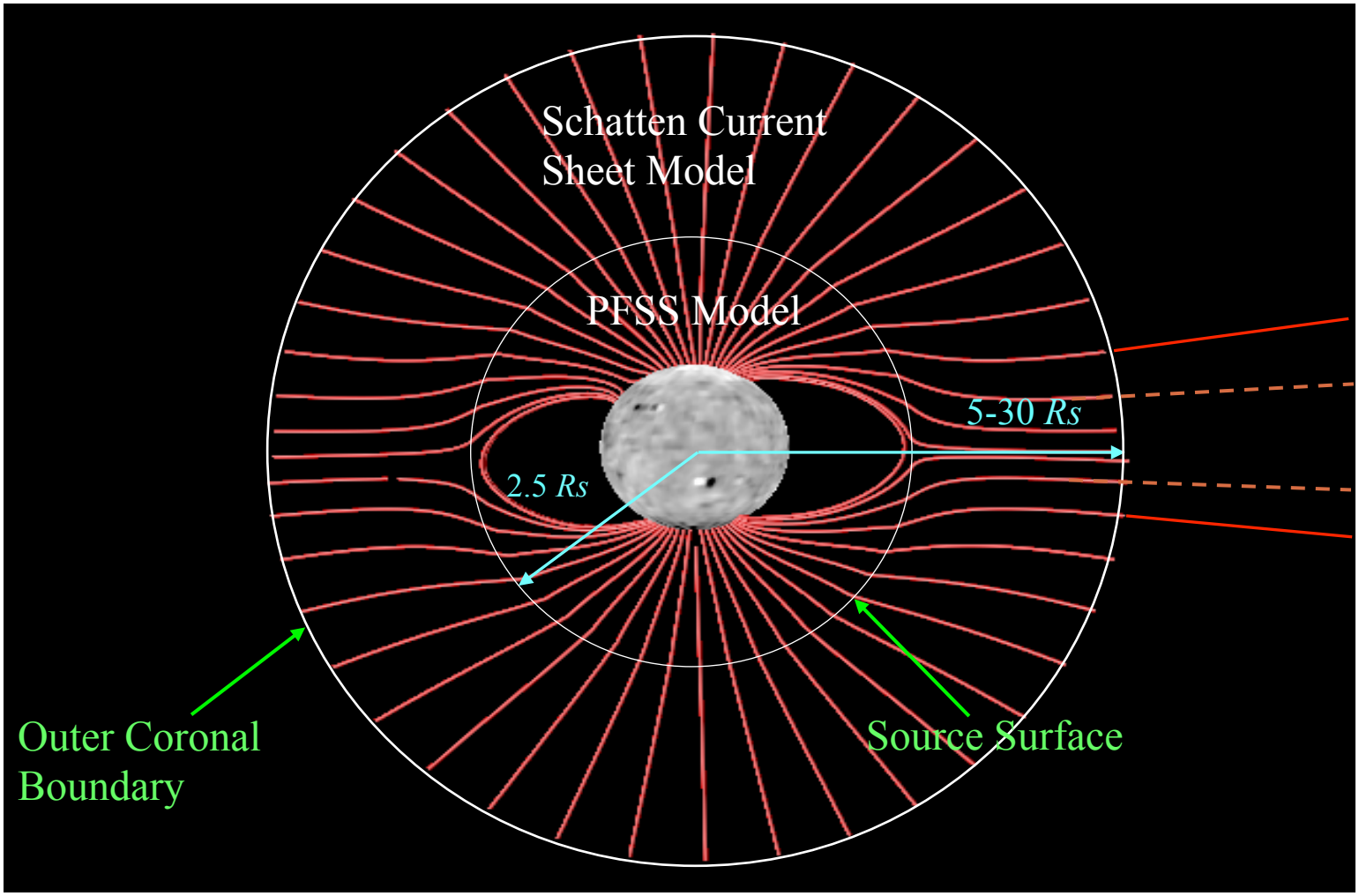


New polarity estimation



New estimation merged with ADAPT map

Wang-Sheeley-Arge (WSA) Model

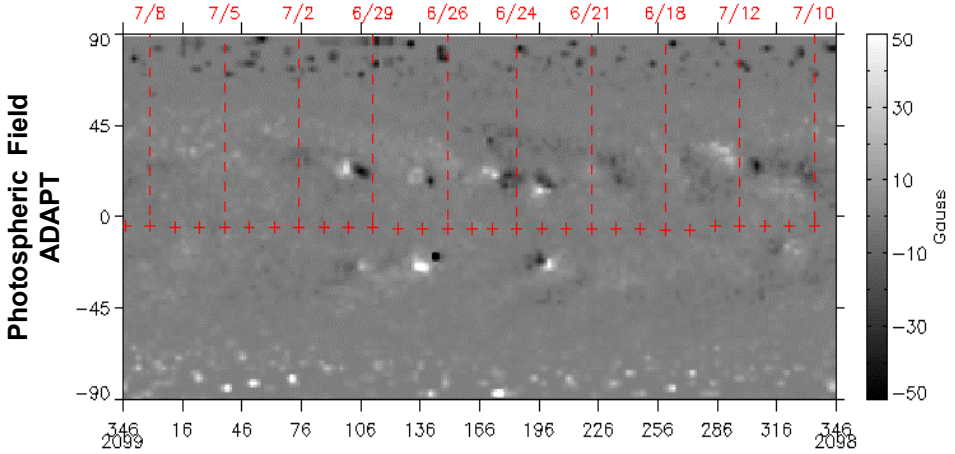


Solar Wind Model (e.g., WSA 1D Kinematic model, ENLIL, HAF, LFM-Helio) (5-30*Rs* to 1AU)

Photospheric Field
(Before & After Far-Side Active Region Insertion)

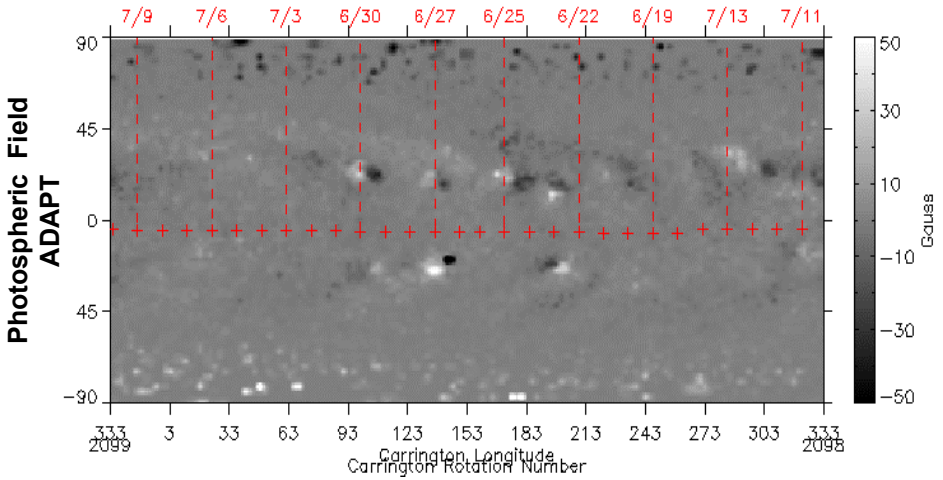
Large, GONG detected far-side active region inserted into the ADAPT map on *July 1, 2010*

June 30, 2010

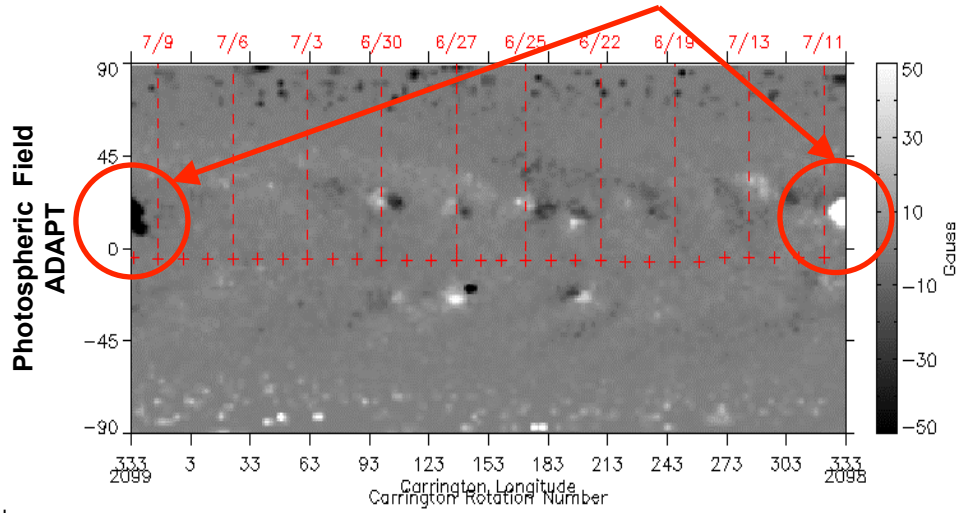


July 1, 2010

WITHOUT **Active Region Inserted**

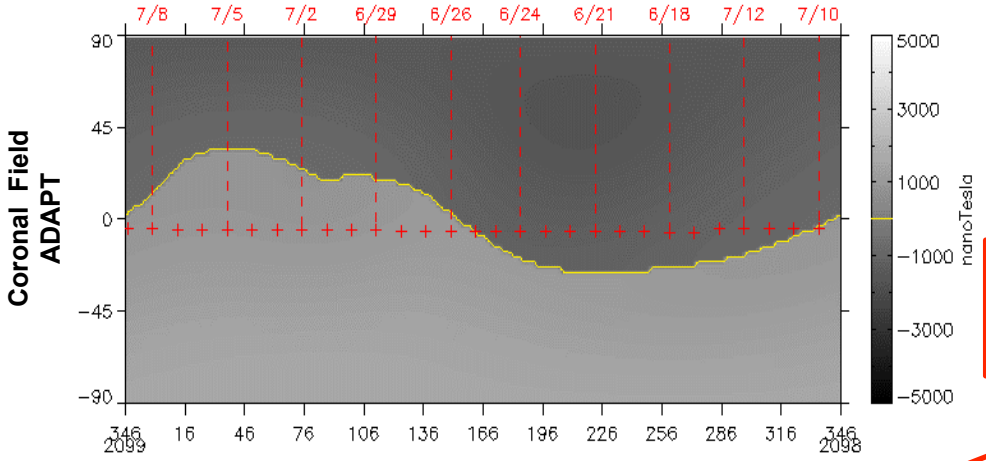


WITH **Active Region Inserted**



Coronal Field at 5 Rs
(Before & After Far-Side Active Region Insertion)

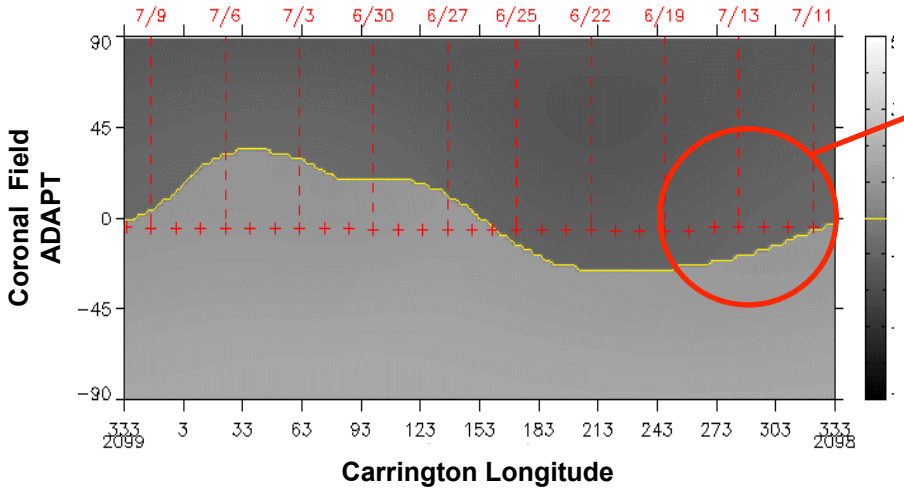
June 30, 2010



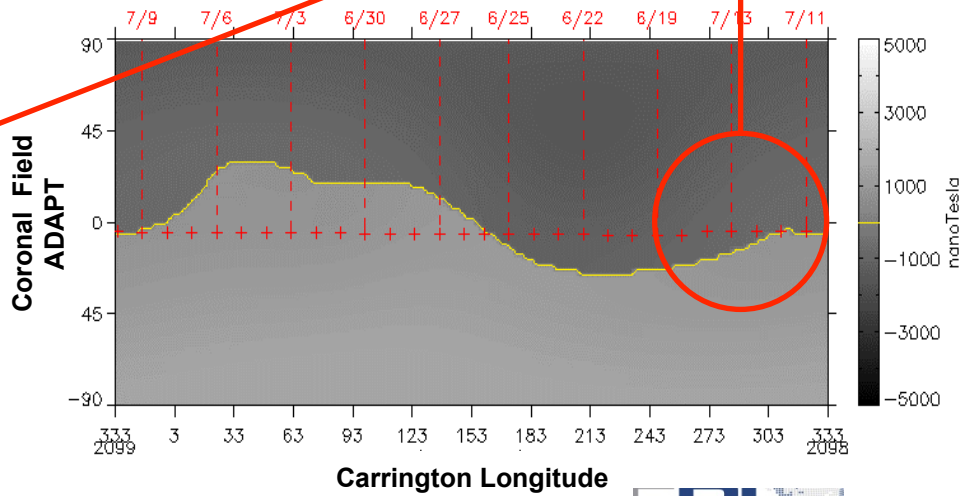
Note Current Sheet changes

July 1, 2010

Without Active Region Inserted



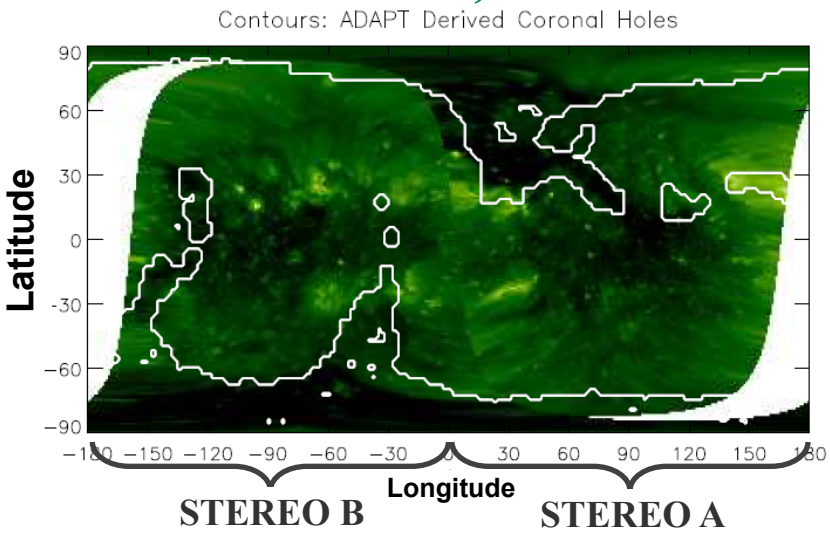
With Active Region Inserted



WSA Model Coronal Holes vs. STEREO EUVI Observations

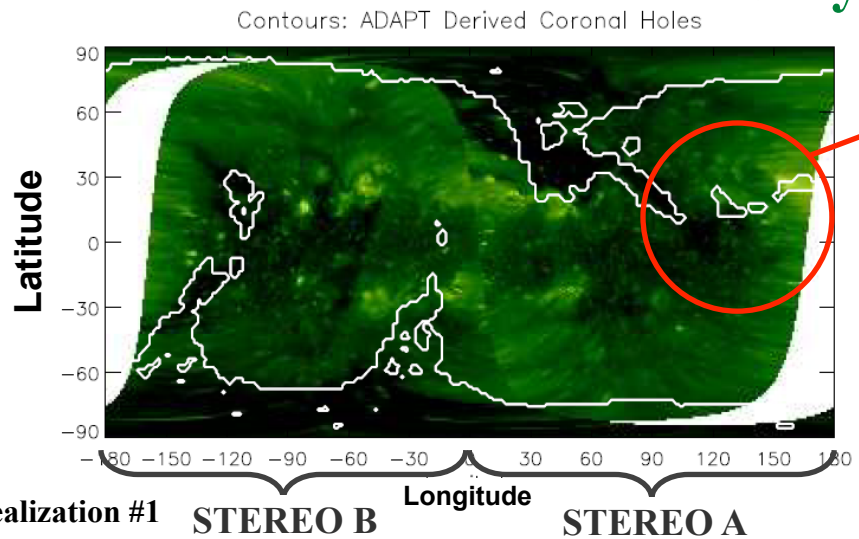
- **WSA Coronal Holes** - White contours
- **STEREO A&B EUVI** - Green areas

June 30, 2010

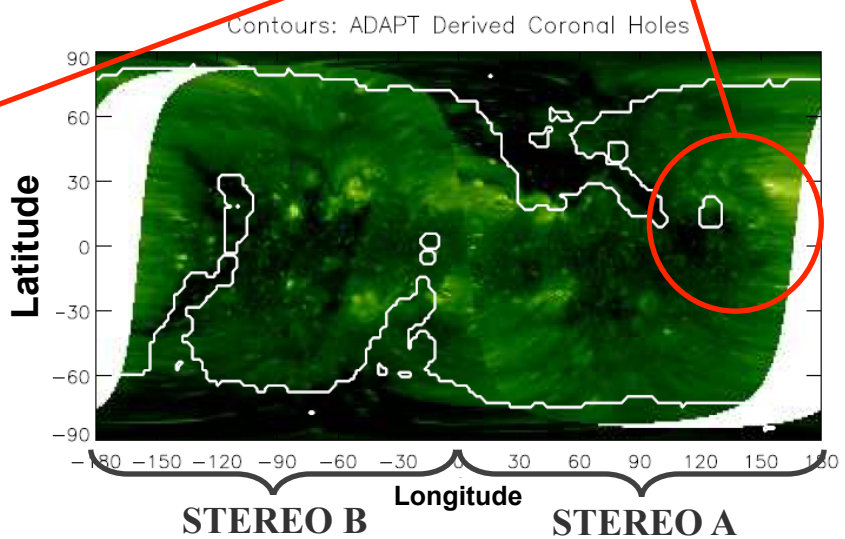


Note coronal hole changes

WITHOUT Active Region Inserted — July 1, 2010



WITH Active Region Inserted

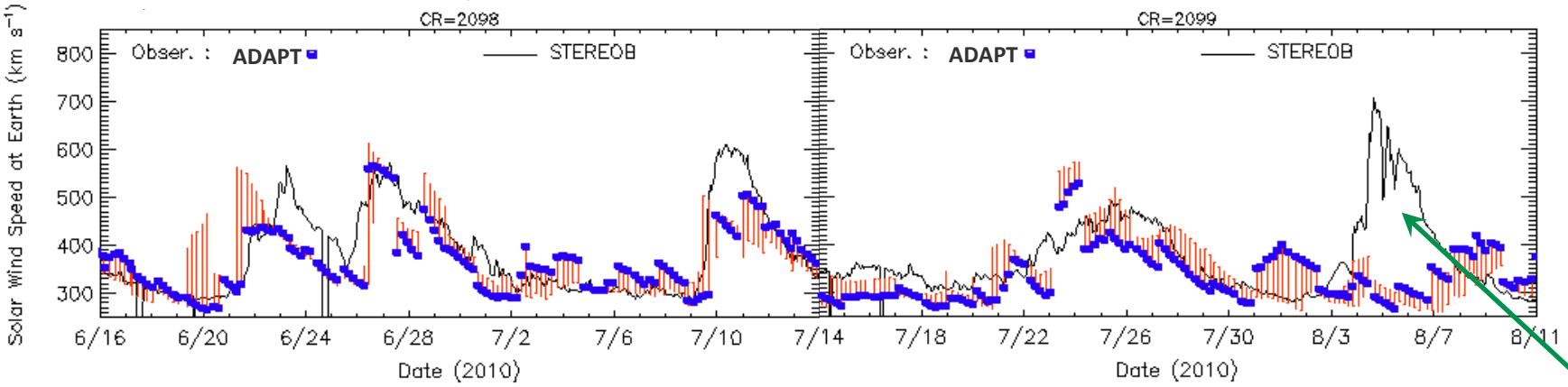


Realization #1

WSA Solar Wind Speed vs Observations at STEREO B (With & Without Far-Side Active Region Inserted)

Without Far-Side Active Region Inserted

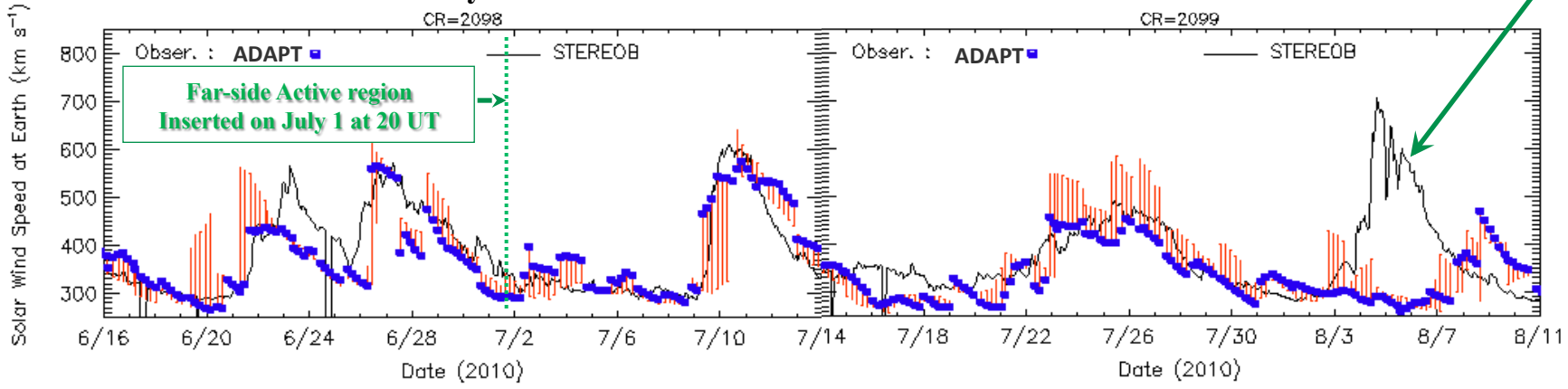
4 Day Advanced Predictions and STEREO B Observations



ICME

With Far-Side Active Region Inserted

4 Day Advanced Predictions and STEREO B Observations



$F_{10.7}$ Empirical Model

The F10.7 empirical model, based on Henney et al. 2012, uses the near-side magnetic field estimates from the ADAPT maps:

$$F_{model} = m_0 + m_1 S_P + m_2 S_A$$

where

Solar radial magnetic field from ADAPT

$$S_P = \frac{1}{\sum \omega_\theta} \sum_{25G<|B_r|}^{|B_r|<150G} |B_r| \omega_\theta$$

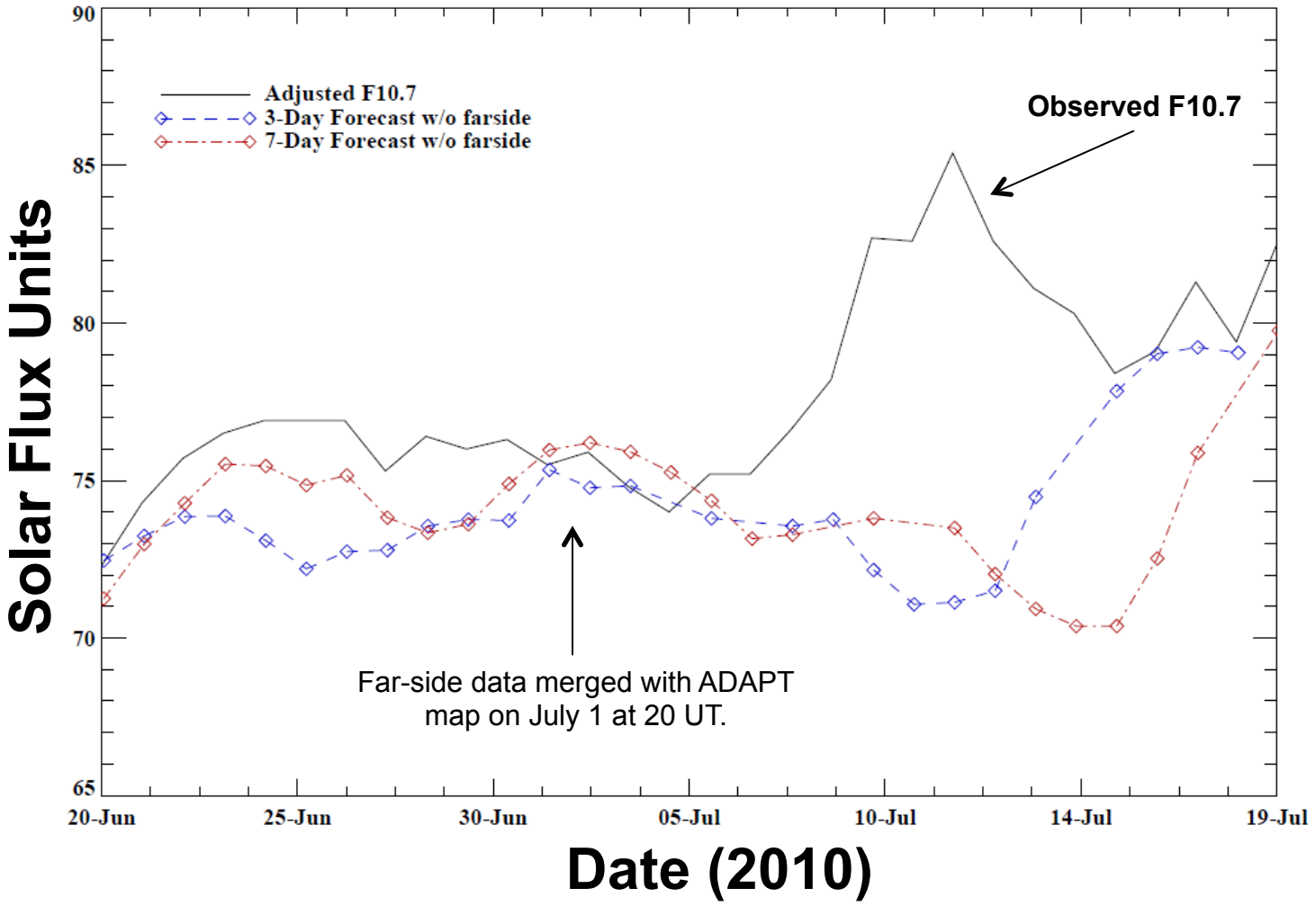
Solar Weak Field ["Plage"]

$$S_A = \frac{1}{\sum \omega_\theta} \sum_{150G \le |B_r|} |B_r| \omega_\theta .$$

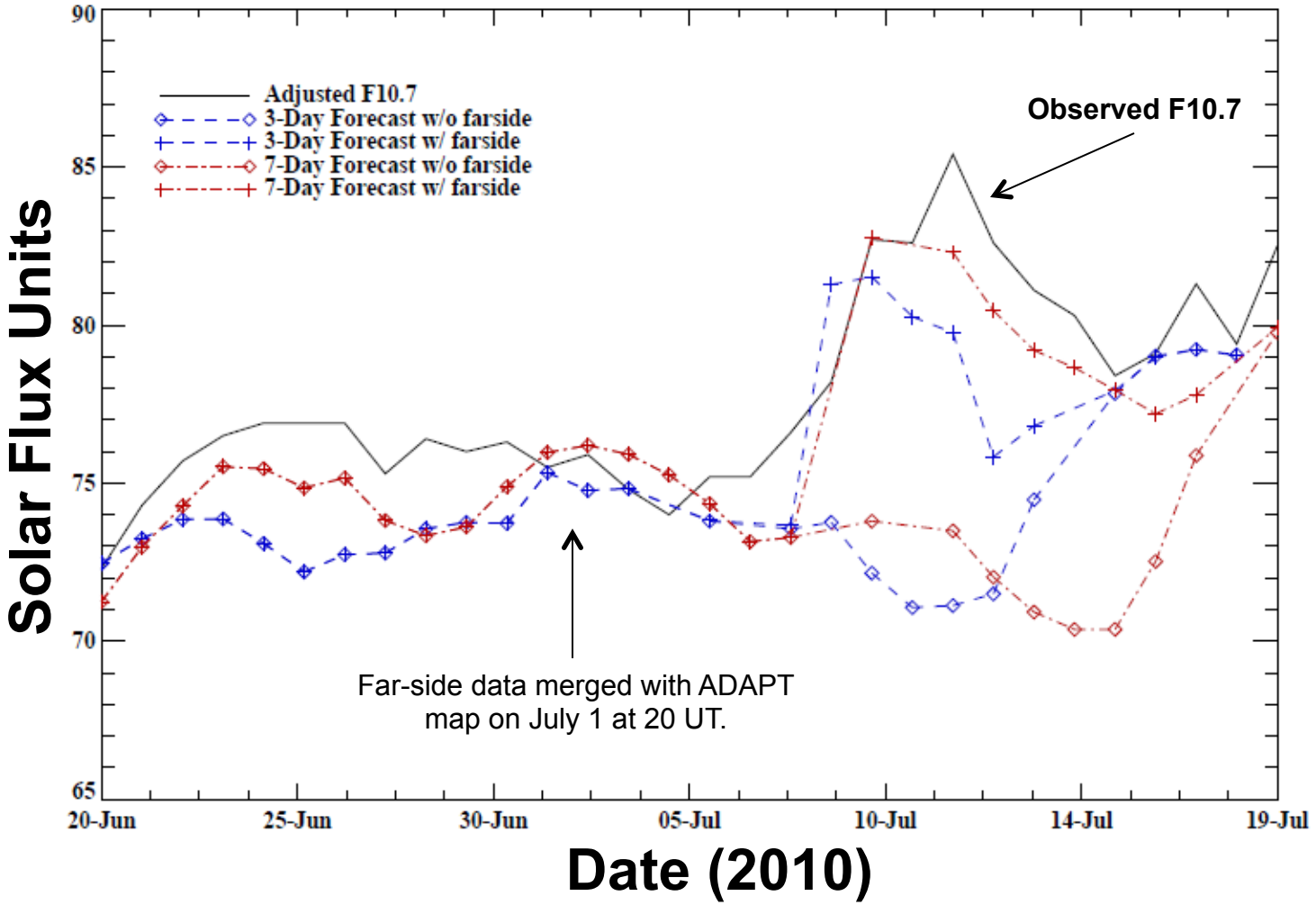
Solar Strong Field ["Sunspot"]

For more details, see: Henney et al. 2012, Space Weather, 10, S02011

$F_{10.7}$ Forecasting w/o Farside



$F_{10.7}$ Forecasting with Farside



Project Objectives & Goals

Project Objectives

ADAPT will be modified to ingest:

- Line-of-sight, for weak field regions, and radial component of the vector, for strong field regions, magnetic data inferred from the SDO/HMI instrument.
- Flux emergence estimates inferred from helioseismic observations.
- Local active region magnetic simulation maps produced by the Flux Emergence Prediction Tool (FEPT) tool.

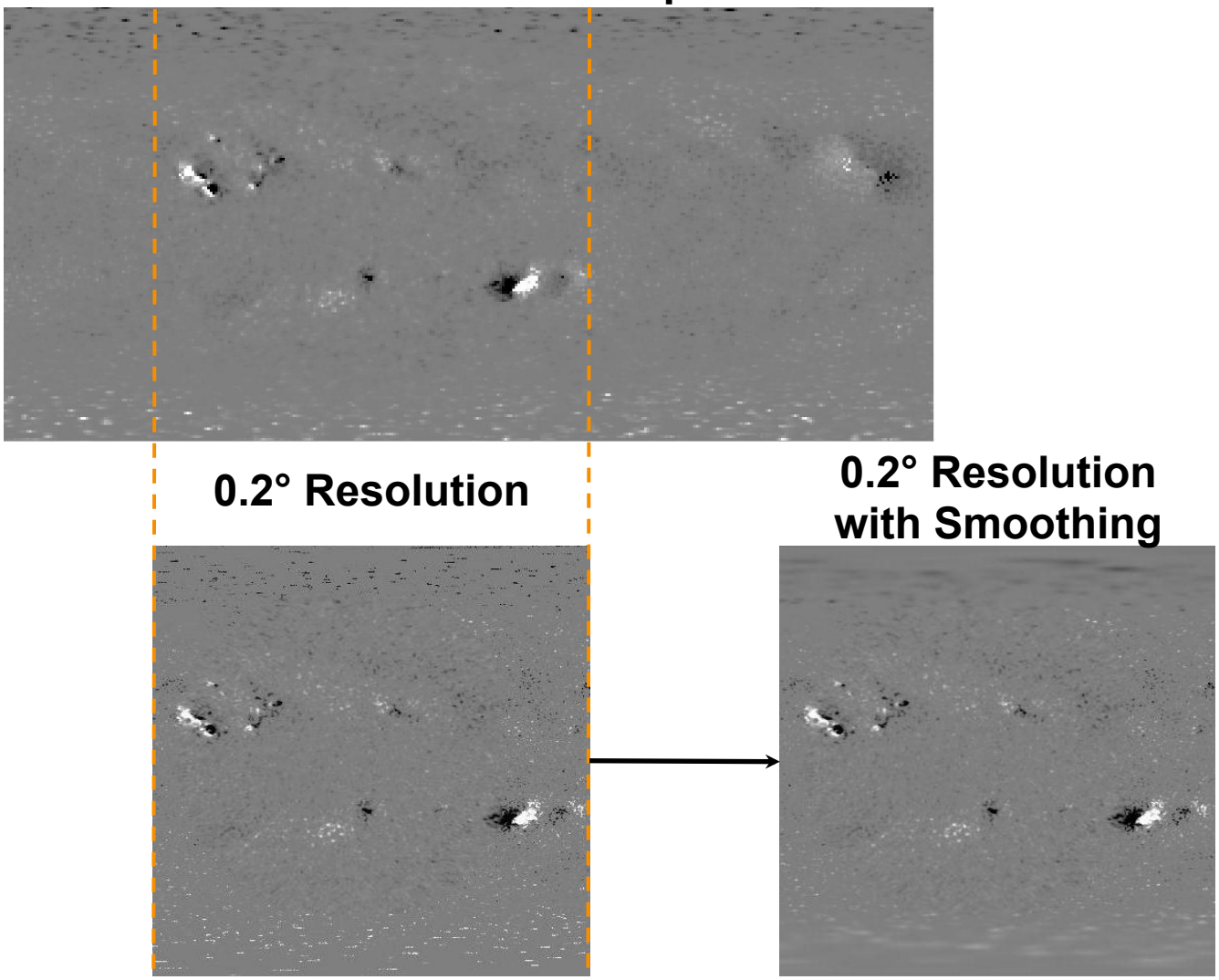
Goals this year:

- modify the ADAPT model to incorporate HMI line-of-site (LOS) maps.
- understand subsurface emerging flux (SEF) data structure & signal nature to begin work to incorporate SEF data into ADAPT.
- The WSA will be modified to include ADAPT-HMI global maps.

Goals Next Year:

- Begin to modify ADAPT to incorporate an ensemble of helioseismic derived emerging flux forecasts.
- Modify (i.e., calibrate) the empirical solar wind relationship used in WSA to work with HMI data.

ADAPT Modified to Incorporate High Res. LOS Magnetograms

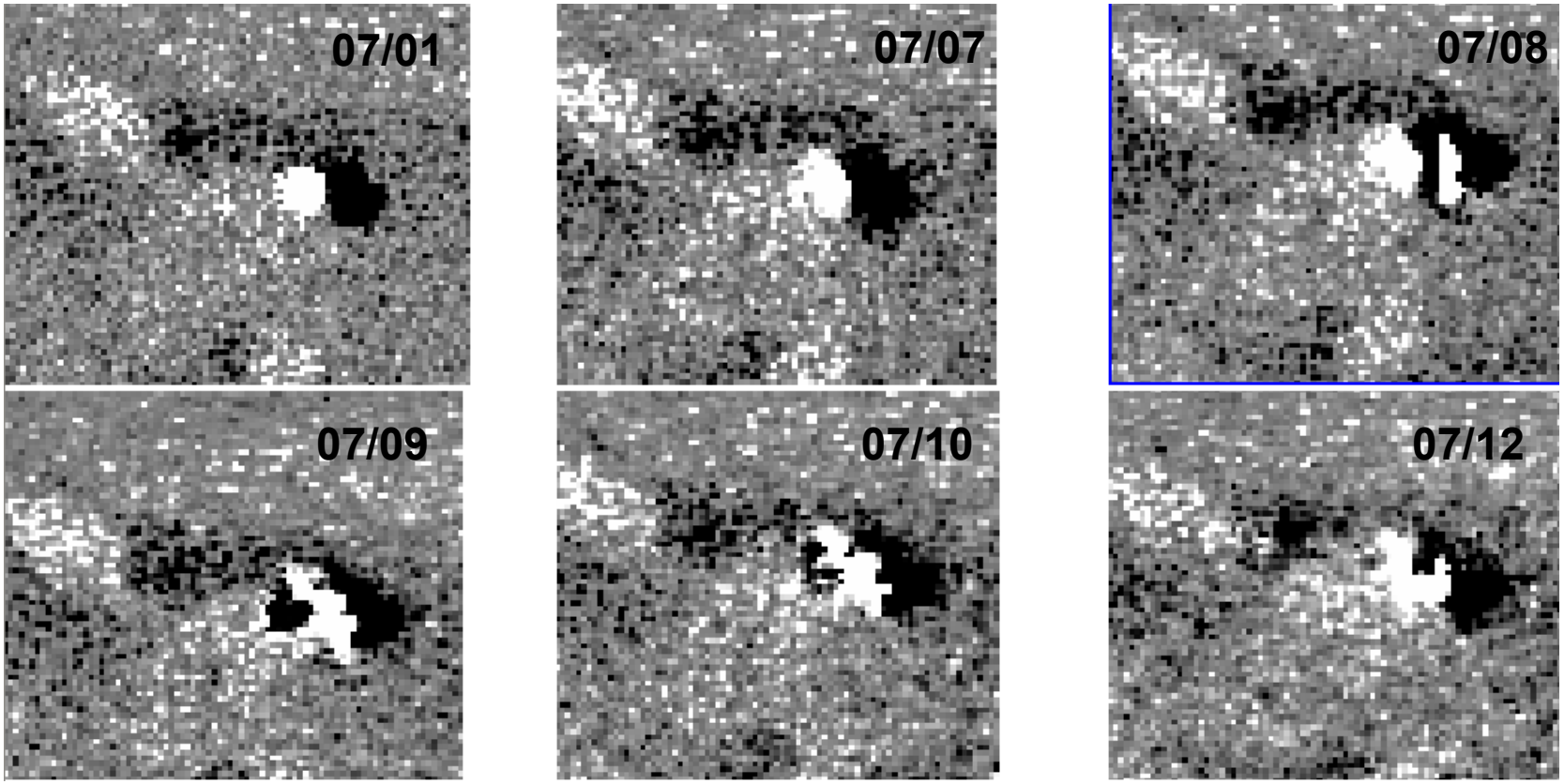


Summary

1. ADAPT is a photospheric magnetic field flux transport model that makes use of rigorous data assimilation methods.
   - Provides “instantaneous snapshots” of the Sun’s global magnetic field as input for coronal, solar wind, and other (e.g., F10.7) models.
2. Implemented & testing the LETKF data assimilation methodology in ADAPT.
3. Incorporating helioseismic far-side active region data into the ADAPT model.
   - Experimenting with methods to realistically represent the range in sizes, orientations, & polarity distributions of far-side detected active regions in the ADAPT ensemble.
   - Preliminary test done for Jul. 1, 2010 GONG far-side active region detection.
     - Promising coronal hole, solar wind, & F10.7 prediction results!
4. ADAPT modified to incorporate high resolution LOS magnetograms.
   - Tested with GONG and VSM magnetograms.
   - Working with Stanford to ingest HMI.
5. Need to understand subsurface emerging flux (SEF) data structure & signal nature to begin work to incorporate SEF data into ADAPT.
6. Coronal & solar wind solutions very sensitive to photospheric mag. field B.C.

Farside Data Assimilation

- Example evolution of the farside signal within ADAPT maps. The farside model estimation is merged on July 1st. The first observation is assimilated on July 8th. The final frame, July 12th, is nearly 100% observation, whereas the July 7th image is 100% far-side & ADAPT flux transport model values.

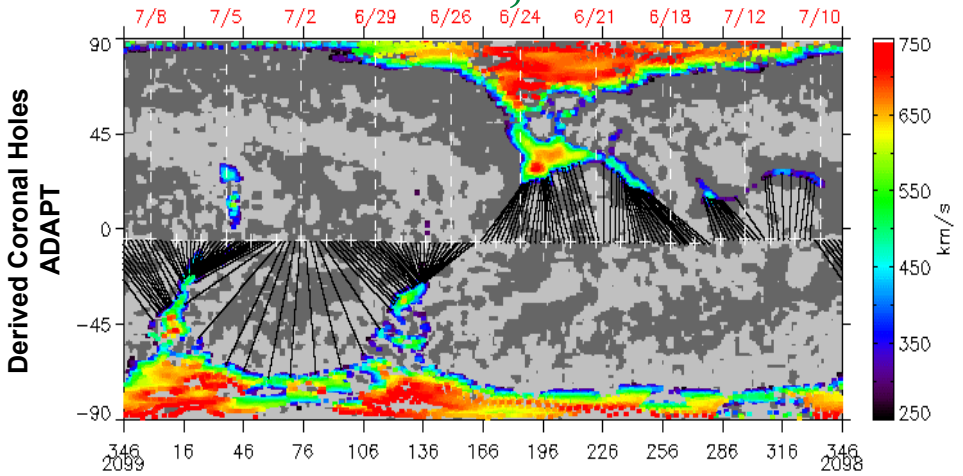


Model Coronal Holes
(Before & After Far-Side Active Region Insertion)

Coronal Holes: Colored Regions

Photospheric Field Polarity: Light/Dark grey scale = Pos./Neg. polarity

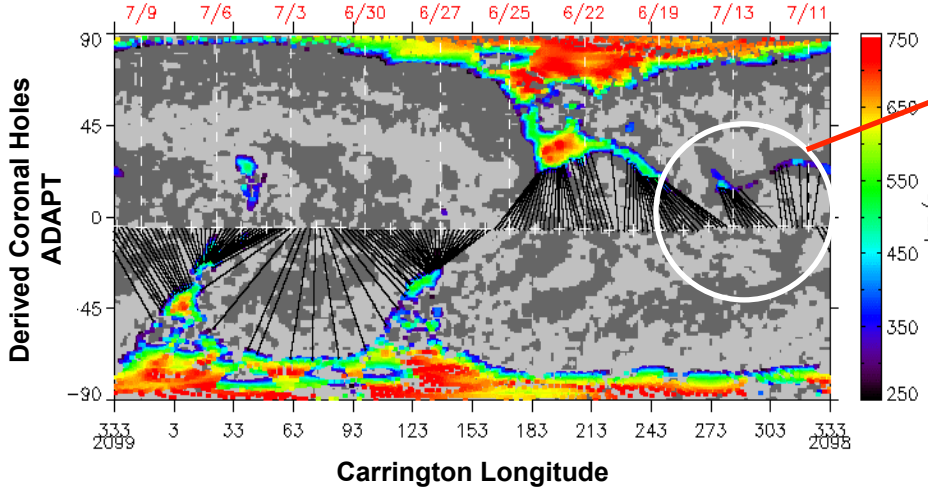
June 30, 2010



Note coronal hole changes

July 1, 2010

Without Active Region Inserted



With Active Region Inserted